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Sugarcane Yield, Sugarcane Quality, and Soil Variability in Louisiana

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ABSTRACT

This study was conducted to determine the extent of temporal and spatial variability present in commercially cultivated sugarcane (interspecific hybrids of *Saccharum* spp. cv. LCP 85-384) grown in South Louisiana. Sugarcane fields at two locations were harvested for three consecutive years (2001–2003) in a grid pattern with a single-row, chopper harvester and a field transport wagon equipped with electronic load sensors to determine cane yields. Sugar yield and quality were determined from a random cane sample from each grid cell, and soil samples were collected after harvest from each grid cell (2002–2004). At each location, the majority of soil properties exhibited nonnormal distributions with coefficients of variation ranging from 1 to 56% over all years and locations, and all soil properties were spatially correlated with the range varying from 26 to 241 m. Cane and sugar yields and sugar quality parameters at both locations were found to exhibit nonnormal distributions in selected years, and the coefficients of variation ranged from 5 to 20% over all years and locations. Cane and sugar yields and quality parameters were spatially correlated with a range varying from 26 to 187 m with the exception of theoretically recoverable sugar and fiber at one location in 2003. Soil S and Ca/Mg ratio were correlated to all sugar parameters at one location, and soil organic matter and soil buffer pH were correlated to all sugar parameters at the second location. These data would indicate that sufficient variability exists in commercially produced Louisiana sugarcane to justify a precision agricultural management approach.

PRECISION AGRICULTURE (PA) has proven to be a valuable management tool for crop producers throughout the country, allowing for increases in profit through more efficient application of crop inputs and mapping of yield and quality variability (Robert et al., 1995, 1996). Several researchers have demonstrated that variable-rate (VR) application methods can reduce the total amount of a nutrient applied to a given field and also reduce variability of that nutrient within the field (Bianchini and Mallarino, 2002; Wittry and Mallarino, 2004). Additional benefits of PA have been suggested and include increased crop quality, improved sustainability, lower management risk, increased food safety due to product traceability, environmental protection, and rural development through new skills transferable to other activities (Bongiovanni and Lowenberg-Deboer, 2004; Robert, 2002). Hatfield (2000) has provided a detailed discussion of the potential benefits of PA to environmental quality in the areas of nutrient management, pest management, and soil and water quality. The author indicated that PA could have a significant positive impact on environmental quality, provided that the necessary research is conducted at the field, farm, and watershed scales.

Despite these potential advantages, adoption of PA techniques by the Louisiana agricultural community is very limited. This may be due, in part, to a lack of PA research in the state, particularly in sugarcane, the state's most valuable row crop commodity. To date, only one Louisiana PA study in sugarcane has been reported in the scientific literature to the authors' knowledge (Johnson and Richard, 2003). In this preliminary, 1-yr study, the authors used yield mapping to determine the extent of variability in sugarcane yield and to relate the observed variability to variation in soil properties. The authors reported that sugarcane expressed a high degree of variability at one location in Terrebonne parish with gross cane yields ranging from 36 to 134 Mg ha^{-1}. Theoretically recoverable sugar (TRS) ranged from 51 to 104 kg Mg^{-1} and sugar yields from 2640 to 14 570 kg ha^{-1} at the same site. At another site in Iberia parish, gross cane yields ranged from 31 to 114 Mg ha^{-1}, TRS from 41 to 115 kg Mg^{-1}, and sugar yields from 3010 to 12 430 kg ha^{-1}. Although this study offered interesting insight into the extent of natural variability present in commercially produced sugarcane in Louisiana, additional data are required to confirm these findings.

Precision agriculture studies have been conducted in other crops in Louisiana, most notably cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), and soybean [*Glycine max* (L.) Merr.]. In a study performed in Winnsboro, LA (Johnson et al., 1999), the authors found that cotton yield and all fiber quality properties measured, with the exception of short-fiber content, displayed spatial correlation. It was also noted that fiber yield was correlated to soil organic matter (OM), B, Cu, Fe, Mn, and Zn. Similar results were reported by these authors in a study conducted in a South Carolina cotton field (Johnson et al., 2002). Moore and Wolcott (2001) investigated the spatial relation among crop yield, soil OM, electrical conductivity, topography, and compaction in six fields cropped to corn and soybean. The authors reported a positive correlation between crop yield and soil electrical conductivity and a negative correlation with elevation. Finally, Anderson et al. (1999) used tree regression and a general linear mixed model that incorporated a spatially varying soil parameter as a covariate to determine the effects of soil variability on sugarcane yield in Florida. Tree regression analysis also indicated that sugarcane yield could be grouped and predicted

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Abbreviations: CEC, cation exchange capacity; CV, coefficient of variation; ENR, estimated nitrogen release; OM, organic matter; PA, precision agriculture; SEK, standard error for kurtosis; SES, standard error for skewness; TRS, theoretically recoverable sugar; VR, variable rate.

using selected soil and crop properties, including soil Ca, soil Mg, soil P, crop age, and water table depth. There have been several reports concerning PA research in sugarcane outside of the USA. Bramley (1999) utilized the differential global positioning system (GPS) and a sugarcane yield monitor to construct yield maps for two first ratoon sugarcane crops in Australia. The author reported significant variability with the cane yield varying from 50 to 150 t ha^{-1} in the first field and from 65 to 150 t ha^{-1} in the second field. Similar results were reported by Cora and Marques (2001), who conducted a study in Brazil to investigate spatial variability in sugarcane yield. The authors reported that cane yield varied from 70 to 200 t ha^{-1} and was accompanied by strong variability in soil chemical properties.

The adoption of PA management techniques in Louisiana sugarcane production systems may offer significant economic advantages to producers, in addition to improving sustainability and minimizing adverse environmental impacts. However, sufficient variability in sugarcane yield and/or quality must be present to justify the PA approach. Thus, the objective of this research was to investigate the extent of temporal and spatial variability in sugarcane yield and quality in relation to variability in soil properties in two fields under commercial production and to determine if sufficient variability is present to justify a PA management approach.

MATERIALS AND METHODS

Field Layout and Soil Analysis

Yield-mapping experiments were conducted for three consecutive growing seasons (2001–2003) at Rebecca Plantation in Schriever, LA, and Gralyn Farms in Patoutville, LA. The site at Rebecca Plantation was 3.24 ha in size and was located in a newly planted sugarcane field (plant cane). The soil at this site was mapped as a Mhoon silt loam (fine-silty, mixed, superactive, nonacid, thermic Fluvaquentic Endoaquepts). The site at Gralyn Farms was 3.65 ha in size and was located in a fourth-ratoon (stubble) crop. It was of interest to include the older ratoon crops because an increased percentage of these crops are being retained for production due partly to the very good rationing ability of the predominant sugarcane variety LCP 85-384. This is particularly true in the northern Louisiana production area where 34.3% of the total crop was in third or older ratoon crops compared with a state average of 26.9% (Legendre and Gravois, 2003). The soil at this site was mapped as a Jeanerette silt loam (fine-silty, mixed, superactive, hyperthermic Typic Argiaquolls). Both sites were planted to sugarcane cultivar LCP 85-384. The experiments were harvested at Rebecca Plantation on 19 Nov. 2001, 11 Dec. 2002, and 13 Nov. 2003, respectively. At Gralyn Farms, the tests were harvested on 18 Dec. 2001, 19 Nov. 2002, and 22 Oct. 2003, respectively. Each field was harvested in a grid cell pattern in which the field was divided into cells with dimensions of 10.6 by 15.2 m, and then each cell was harvested with a single-row, chopper harvester (Cameco CH2500, Cameco Industries, Thibodaux, LA). Sugarcane stalks harvested with this system are separated from excess leaf material and sectioned into 15- to 25-cm pieces called billets. Plot weights were determined using a single-axle high dump billet wagon containing three electronic load sensors (Cameco Industries, Thibodaux, LA). The load sensors were mounted on the spindles at the end of the axle and on the wagon's tongue where it was connected to the tractor. The "weigh wagon" was also equipped with a billet sampler. In addition to weights, a grab sample of sugarcane billets was obtained from each grid cell as they were pouring into the wagon for sugar quality analysis. Soil samples (0–20 cm) were also collected early in 2002, 2003, and 2004 for the 2001, 2002, and 2003 crops, respectively. In 2002, all grid cells were sampled at Rebecca Plantation, and alternating grid cells (odd numbered) were sampled at Gralyn Farms. In 2003 and 2004, all cells were sampled at both Gralyn Farms and Rebecca Plantation. Samples were air-dried, ground with a Straub 4-E electric grinding mill and shipped for analysis at A&L laboratories (Memphis, TN). Soil properties determined included soil OM, soil estimated N release (ENR), soil pH, soil buffer pH, exchangeable cations (Ca, Mg, and K), soil cation exchange capacity (CEC), soil P, and soil S. Phosphorus and major cations present in soil samples were estimated using the Mehlich 3 extraction procedure and inductively coupled plasma-atomic emission spectrophotometry (USEPA Method 200.7), respectively. Soil OM was determined by Walkley–Black oxidation (Nelson and Sommers, 1996). Soil pH was determined in a 1:1 soil-to-water suspension and soil buffer pH using the Shoemaker, McLean, and Pratt buffer (Thomas, 1996). The soil ENR is calculated from the soil OM and estimated texture, and the soil CEC is calculated by summing exchangeable cations.

Statistical Analysis

Exploratory and descriptive analyses of sugar and soil data were performed by first calculating univariate statistics (PROC UNIVARIATE, SAS Inst., Cary, NC). Skewness and kurtosis coefficients were considered to be significant if their absolute values were greater or equal to 2 times the standard errors for skewness and kurtosis, respectively (Tabachnick and Fidell, 1996). The standard error for skewness (SES) was calculated as SES $= (6/n)^{1/2}$, and the standard error for kurtosis (SEK) was calculated as SEK $= (24/n)^{1/2}$, where n = the sample number (Tabachnick and Fidell, 1996). The Shapiro–Wilkes statistic was also calculated for all of the sugar and soil data to test for the presence of a normal distribution. If the calculated W statistic was significant at $P \leq 0.05$, the distribution was considered nonnormal (SAS Inst., 2004). To test for the presence of spatial trends, variogram analysis was performed (GS+, Gamma Design Software, Plainwell, MI). Before variogram analysis, three-dimensional surface plots were constructed for each variable (SAS PROC GRID, PROC 3D). This information was used to determine the strategy for variogram analysis. When an obvious linear trend existed in the variable, spatial data were detrended by fitting a plane surface through each data set (SAS PROC REG), evaluating the surface at each data point, and subtracting the surface from the raw data (Sadler et al., 1998). The variogram was then calculated from the residual values. For other variables, it was not possible to fit a simple linear trend. In this case, a decreased search neighborhood was utilized to construct variograms by limiting the maximum lag distance used in the analysis. The maximum lag distance is the maximum distance between points used in calculation of the variogram. Both of these procedures were used to account for the apparent nonstationarity present in the experimental site. An underlying assumption of the sample variogram is that of a constant mean with the covariance function dependent only on the distance separating the points, not the direction (Kitanidis, 1997). The presence of a trend in the data would invalidate these assumptions. Simple correlation analysis was performed between soil and sugar properties on the combined data set (combined over years 2001, 2002, and 2003 for each location) with SAS PROC CORR.

Correlation results were considered significant if the probability was significant at $P \leq 0.05$. Finally, maps were constructed by block kriging [Surfer, Golden Software, Golden CO] utilizing the previously determined variograms to determine if spatial patterns existed within each field.

RESULTS AND DISCUSSION

Soil Properties

Univariate Statistics

In the 2002 samples from Rebecca Plantation, soil K, soil Mg, and CEC exhibited normal distributions (Table 1). The remaining soil properties did not have normal distributions as determined from the Shapiro–Wilkes statistic. The majority of these properties also exhibited a significant positive skew ($2 \times$ SES = 0.33) with the mean greater than the median. Soil K, Mg, CEC, and S were not significantly skewed. The majority of properties also possessed significant kurtosis values ($2 \times$ SEK = 0.67) with soil K, Mg, CEC, and S not being significantly kurtotic (Table 1). The coefficients of skewness and kurtosis values describe the shape of the sample distribution. A positive skew indicates asymmetry in the distribution with the higher data values tailing to the right, and a negative skew represents lower values tailing left (Goovaerts, 1997). Kurtosis describes the relative size of the distribution's tails. A positive kurtosis value indicates that the distribution is peaked, and a negative value indicates a relatively flat distribution. Taken together, these values describe the conformity of the data to a normal distribution. The coefficient of variation (CV) for the properties measured ranged from 1% for soil buffer pH to 47% for soil P (Table 1), indicating that low-to-moderate variability existed in the data. In the 2003 samples from Rebecca Plantation, only soil Mg and CEC exhibited normal distributions. All properties were also significantly skewed ($2 \times$ SES = 0.33) with the means smaller than the median with the exception of CEC. Soil P, Ca, pH, Ca/Mg ratio, and S exhibited significant kurtosis ($2 \times$ SEK = 0.67) with the remaining properties not showing significant kurtosis. The coefficients of variation observed in the 2003 samples were similar to those obtained in 2002, with ranges varying from 0.9% for soil buffer pH to 50% for soil P (Table 1). Finally, in 2004 at Rebecca Plantation, only soil K exhibited a normal distribution. The majority of soil properties were also significantly skewed and kurtotic. The coefficients of variation were similar to

Table 1. Univariate statistics for soil chemical properties from Rebecca Plantation in 2002, 2003, and 2004.

Soil property	Mean	Median	CV	Skew†	Kurtosis†	Normality‡
			2002 (n = 216, buffer pH n = 151)			
P (mg kg^{-1})	49.2	45.5	47.4	1.19	2.83	0.928***
K (mg kg^{-1})	325.1	325.5	18.0	−0.14	−0.12	0.994^{NS}
Ca (mg kg^{-1})	3473	3394	15.3	1.46	4.17	0.914***
Mg (mg kg^{-1})	780.1	781.5	12.9	−0.02	−0.52	0.992^{NS}
Soil pH	6.26	6.20	6.45	0.59	0.67	0.972**
Soil buffer pH	6.62	6.61	0.99	0.46	1.69	0.972**
Organic matter (%)	1.50	1.40	27.0	1.61	3.65	0.863***
ENR§	73.9	72.0	10.9	1.61	3.65	0.863***
CEC (cmol kg^{-1})¶	23.3	23.2	12.2	0.01	0.13	0.993^{NS}
Ca/Mg	4.47	4.39	12.7	3.51	19.6	0.718***
S (mg kg^{-1})	6.51	6.00	42.1	0.31	−0.43	0.970**
			2003 (n = 216, buffer pH n = 146)			
P (mg kg^{-1})	37.3	34.0	50.09	1.03	1.79	0.934***
K (mg kg^{-1})	349.6	353.0	18.8	−0.44	0.26	0.982**
Ca (mg kg^{-1})	4083	4064	14.2	0.70	1.25	0.973***
Mg (mg kg^{-1})	861.3	864.5	14.7	−0.12	−0.12	0.996^{NS}
Soil pH	6.34	6.00	5.81	1.21	2.97	0.915***
Soil buffer pH	6.65	6.66	0.94	−0.50	0.50	0.980*
Organic matter (%)	1.98	1.90	36.3	061	−0.01	0.961***
ENR	83.6	82.0	17.3	0.59	0.04	0.962***
CEC (cmol kg^{-1})	26.4	26.5	13.5	−0.29	−0.19	0.989^{NS}
Ca/Mg	4.78	4.76	13.2	3.16	17.7	0.760***
S (mg kg^{-1})	7.07	7.00	38.5	0.82	1.14	0.948***
			2004 (n = 216, buffer pH n = 196)			
P (mg kg^{-1})	40.4	37.5	48.9	1.38	4.18	0.914***
K (mg kg^{-1})	324.0	327.0	20.4	0.04	−0.12	0.996^{NS}
Ca (mg kg^{-1})	3775	3651	19.6	0.49	2.70	0.947***
Mg (mg kg^{-1})	846.1	836.5	21.2	0.07	3.31	0.960***
Soil pH	6.03	6.00	5.84	2.39	1.08	0.933***
Soil buffer pH	6.65	6.67	1.66	−1.39	2.74	0.901***
Organic matter (%)	2.36	2.30	45.5	0.45	0.61	0.982**
ENR	91.1	90.0	23.7	0.41	0.63	0.984*
CEC (cmol kg^{-1})	26.5	26.2	16.7	0.68	1.83	0.974***
Ca/Mg	4.46	4.36	14.9	2.34	26.0	0.646***
S (mg kg^{-1})	10.1	10.0	37.4	0.19	−0.48	0.986*

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Skewness and kurtosis statistics: If the absolute value ≥ 2 times the standard error, then the statistic is significant where the standard error of skewness = $(6/n)^{1/2}$ and the standard error of kurtosis = $(24/n)^{1/2}$.
‡ Normality as estimated from the Shapiro–Wilkes test (W, $P < W$). If the test statistic W is significant, then the distribution is not normal.
§ ENR, estimated N release.
¶ CEC, cation exchange capacity.

those observed in 2002 and 2003 with a range of 1.7% for soil buffer pH to 49% for soil P (Table 1).

At Gralyn Farms in 2002, all soil properties, with the exception of soil CEC and soil buffer pH, exhibited nonnormal distributions as determined from the Shapiro–Wilkes statistic (Table 2). Soil P, K, Ca, Mg, S, and the Ca/Mg ratio were significantly skewed ($2 \times \mathrm{SES} = 0.44$), and the majority of soil properties were also significantly kurtotic ($2 \times \mathrm{SEK} = 0.88$). The CV for the properties measured ranged from 1.5% for soil buffer pH to 50% for soil Ca/Mg ratio (Table 2). In the 2003 samples from Gralyn Farms, only soil buffer pH exhibited a normal distribution. In 2003, all properties were significantly skewed with the exception of soil pH and buffer pH. Significant kurtosis was also exhibited by a majority of properties. The CV ranged from 1.2% for soil buffer pH to 56% for soil Ca/Mg ratio. In 2004 at Gralyn Farms, only soil OM and soil ENR displayed normal distributions with a majority of soil properties showing significant skew and kurtosis. The CV ranged from 1.5% for soil buffer pH to 48% for soil Ca/Mg ratio (Table 2).

In general, the data from Gralyn Farms and Rebecca Plantation exhibited similar trends with the majority of soil properties exhibiting nonnormal distributions and significant positive skews and kurtosis values. There were however, some interesting exceptions, particularly when comparing coefficients of variation between the two locations. In 2002, 2003, and 2004, the magnitude of the CVs for soil Ca and soil Mg was two times greater at Gralyn Farms than at Rebecca Plantation, with the exception of soil Mg at Gralyn in 2004, which was slightly less than two times greater (Tables 1 and 2). A similar trend was seen in the values for soil pH and soil CEC. In contrast, at Rebecca Plantation, the magnitude of the CVs for soil OM were almost two times greater than those at Gralyn Farms. These data demonstrate that there is substantial variability present at both locations, and it is consistently expressed over time. These data also demonstrate the importance of taking a site-specific approach as different properties exhibit the greatest variability at each location.

Spatial Variability

The spatial correlation present in the soil data will be summarized using variograms. The variogram measures the average dissimilarity between data points separated by a given distance (Goovaerts, 1997). The graphical vario-

Table 2. Univariate statistics for soil chemical properties from Gralyn Farms in 2002, 2003, and 2004.

Soil property	Mean	Median	CV	Skew†	Kurtosis	Normality‡
			2002 (n = 125, buffer pH n = 73)			
P (mg kg^{-1})	25.3	26.0	47.7	0.98	3.42	0.948***
K (mg kg^{-1})	133.0	127.0	22.3	1.00	1.92	0.944***
Ca (mg kg^{-1})	2969	2764	42.7	0.90	0.79	0.949***
Mg (mg kg^{-1})	383.1	358.0	30.4	1.16	1.61	0.922***
Soil pH	6.21	6.20	14.0	0.14	−1.25	0.945***
Soil buffer pH	6.65	6.65	1.53	0.04	0.13	0.994^{NS}
Organic matter (%)	1.01	1.10	16.4	0.36	0.79	0.843***
ENR§	64.1	66.0	5.20	0.31	0.88	0.845***
CEC (cmol kg^{-1})¶	17.48	17.40	24.2	0.34	0.56	0.989^{NS}
Ca/Mg	8.13	6.91	50.3	1.96	4.57	0.802***
S (mg kg^{-1})	7.53	7.00	36.6	1.68	5.60	0.879***
			2003 (n = 250, buffer pH n = 119)			
P (mg kg^{-1})	20.9	20.0	53.8	0.83	1.31	0.953***
K (mg kg^{-1})	108.8	106.0	15.3	0.50	0.04	0.981*
Ca (mg kg^{-1})	2941	2748	45.9	2.22	9.89	0.846***
Mg (mg kg^{-1})	398.4	373.5	27.8	1.21	1.48	0.909***
Soil pH	6.53	6.50	13.2	−0.06	−1.24	0.951***
Soil buffer pH	6.59	6.58	1.19	0.23	−0.61	0.982^{NS}
Organic matter (%)	2.42	2.50	19.4	−0.31	−0.35	0.984**
ENR	92.4	94.0	10.2	−0.31	−0.35	0.984**
CEC (cmol kg^{-1})	16.5	16.1	28.9	2.26	11.88	0.851***
Ca/Mg	7.76	6.42	55.7	3.04	13.49	0.723***
S (mg kg^{-1})	8.37	8.00	25.7	0.90	3.11	0.942***
			2004 (n = 250, buffer pH n = 98)			
P (mg kg^{-1})	17.1	16.0	44.2	0.85	0.99	0.954***
K (mg kg^{-1})	123.3	120.0	22.3	0.24	−0.79	0.976***
Ca (mg kg^{-1})	3185	3026	39.8	0.91	0.93	0.947***
Mg (mg kg^{-1})	381.8	347.5	28.4	1.27	1.03	0.874***
Soil pH	6.73	6.70	12.3	−0.11	−1.28	0.943***
Soil buffer pH	6.67	6.68	1.52	−0.72	1.44	0.966*
Organic matter (%)	2.41	2.40	24.3	0.14	0.19	0.994^{NS}
ENR	92.1	92.0	12.7	0.13	0.22	0.994^{NS}
CEC (cmol kg^{-1})	17.0	16.6	26.7	0.70	0.82	0.969***
Ca/Mg	8.75	7.49	47.5	1.80	4.13	0.832***
S (mg kg^{-1})	8.23	8.00	33.2	0.86	0.15	0.921***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† Skewness and kurtosis statistics: If the absolute value ≥ 2 times the standard error, then the statistic is significant where the standard error of skewness = $(6/n)^{1/2}$ and the standard error of kurtosis = $(24/n)^{1/2}$.
‡ Normality as estimated from the Shapiro–Wilkes test (W, $P < W$). If the test statistic W is significant, then the distribution is not normal.
§ ENR, estimated N release.
¶ CEC, cation exchange capacity.

gram provides a summary of measured spatial structure of a given property within the experimental location. The experimental variogram, which is computed from the data, is usually described or "fit" to a theoretical variogram model (Kitanidis, 1997). One important feature of the variogram is the range. The range is the maximum distance at which spatial correlation is observed. The variogram plot exhibits a plateau at this distance.

The soil variogram analysis for Rebecca Plantation and Gralyn Farms for the 2002, 2003, and 2004 sampling dates are presented in Table 3. All soil properties investigated, at each location and year, exhibited spatial correlation. The spatial dependence was satisfactorily described with isotropic variograms although a small degree of anisotropy was suggested. Isotropic, or omnidirectional, variograms describe the spatial structure in any direction. Anisotropic variograms, or directional variograms, describe the structure in one direction (Isaaks and Srivastava, 1989). If significant anisotropy exists in the data, then a series of directional variograms would be necessary. The variogram models that described the individual soil properties varied between the two locations and between the individual properties investigated although it was only necessary to utilize the exponential and spherical variogram to describe the data. For example, in 2002, the variogram model for soil P was exponential with a range of 80 m at Rebecca Plantation and spherical with a range of 204 m at Gralyn Farms (Table 3). At Rebecca, in 2002, the majority of soil properties were described by spherical variograms (exceptions P, K, and buffer pH) and possessed a range of spatial correlation varying from 29.4 m for soil OM to 138 m for soil Mg. The variogram data from Rebecca Plantation in 2003 were similar to those observed in 2002 with the majority of the data described by spherical variograms. The ranges of spatial correlation were also similar with several noted exceptions. The ranges for soil K and soil Ca/Mg ratio increased, and the ranges for soil P and S decreased. In 2004 at Rebecca, the ranges for soil K, soil pH, and soil Ca continued to increase while the ranges for soil Mg, soil buffer pH, and soil CEC remained relatively stable (Table 3).

Table 3. Semivariance parameters for soil chemical properties from Rebecca Plantation and Gralyn Farms in 2002, 2003, and 2004.

	Rebecca†				Gralyn#			
Soil property	**Ptrt‡**	**Mlag§**	**Model¶**	**Range**	**Ptrt**	**Mlag**	**Model**	**Range**
		m		m		m		m
				2002				
P (mg kg^{-1})	D	226	E	80.1	ND	306	S	203.6
K (mg kg^{-1})	D	100	E	60.0	ND	200	S	77.9
Ca (mg kg^{-1})	ND	100	S	37.8	ND	306	S	116.6
Mg (mg kg^{-1})	ND	226	S	138.0	ND	250	S	193.2
Soil pH	ND	226	S	95.0	ND	306	S	111.4
Soil buffer pH	ND	226	E	50.7	ND	306	E	90.9
Organic matter (%)	ND	226	S	29.4	ND	306	E	71.7
ENR††	ND	226	S	29.5	ND	306	E	72.0
CEC (cmol kg^{-1})‡‡	D	226	S	36.3	ND	306	S	127.0
Ca/Mg	D	100	S	38.2	ND	200	S	116.8
S (mg kg^{-1})	ND	125	S	89.0	D	300	S	240.9
				2003				
P (mg kg^{-1})	D	100	E	41.1	ND	306	S	160.7
K (mg kg^{-1})	D	226	E	156.6	ND	200	S	135.9
Ca (mg kg^{-1})	D	100	E	63.3	ND	200	S	94.8
Mg (mg kg^{-1})	ND	226	S	128.1	ND	200	S	161.7
Soil pH	ND	226	S	115.7	ND	306	S	121.2
Soil buffer pH	ND	226	S	48.7	ND	306	S	171.3
Organic matter (%)	ND	100	S	32.2	ND	306	S	146.4
ENR	ND	100	S	32.1	ND	306	S	146.8
CEC (cmol kg^{-1})	D	226	E	46.8	ND	200	S	102.0
Ca/Mg	ND	226	S	192.5	ND	200	S	95.7
S (mg kg^{-1})	D	100	S	25.9	ND	306	S	166.1
				2004				
P (mg kg^{-1})	D	100	S	40.3	ND	306	S	224.6
K (mg kg^{-1})	D	226	E	207.0	ND	200	S	141.9
Ca (mg kg^{-1})	ND	226	S	136.7	ND	306	S	115.4
Mg (mg kg^{-1})	ND	226	S	131.5	D	250	S	156.7
Soil pH	ND	226	S	121.0	ND	306	S	123.1
Soil buffer pH	D	226	E	39.3	ND	306	S	169.3
Organic matter (%)	D	226	S	70.9	ND	306	S	110.8
ENR	D	226	S	69.6	ND	306	S	109.8
CEC (cmol kg^{-1})	D	226	E	30.9	ND	306	S	125.6
Ca/Mg	ND	226	S	138.5	ND	200	S	106.9
S (mg kg^{-1})	D	100	S	30.7	ND	200	S	159.4

† n = 216 for Rebecca in 2002, 2003, and 2004.
‡ Ptrt, data set pretreatment. D = data set detrended by fitting plane surface, subtracting trend, and performing variogram analysis on residuals; ND = not detrended.
§ Mlag, maximum lag distance used in variogram fitting.
¶ Proposed variogram model. E = exponential; S = spherical.
# n = 125 for Gralyn in 2002 and n = 250 for Gralyn in 2003 and 2004.
†† ENR, estimated N release.
‡‡ CEC, cation exchange capacity.

At Gralyn, in 2002, the majority of properties were described by the spherical model (exceptions buffer pH, OM, and ENR) with ranges varying from 72 m for soil buffer pH to 241 m for soil S (Table 3). In 2003, all of the data were described by spherical variograms (Table 3). The ranges of spatial correlation were also similar with the exception of soil K, OM, and ENR, which approximately doubled in 2003. Finally, in 2004, all of the soil properties were described by spherical variograms and only the ranges for soil K and soil pH continued to increase while the range for soil Mg decreased slightly (Table 3).

A distinctive difference in the range of spatial correlation was observed between the two locations. At Gralyn Farms, a greater range of spatial correlation was found for all soil properties in 2002, for all properties except soil K and Ca/Mg ratio in 2003, and for all properties except soil K, soil Ca, and soil Ca/Mg ratio in 2004. A possible explanation for this effect may be related to crop age. The sugarcane at Gralyn Farms was a fourth-ratoon crop. The soil at this site has been subjected to in-row cultivation between crops, but the crop rows had been present for over 7 yr by 2004. The sugarcane at Rebecca Plantation was a "plant-cane" crop. The soil at this site was thoroughly mixed during removal of the old ratoon crop and the repeated cultivations before row building. We suggest that the observed soil spatial variability increases due to the lack of cultivation in these fields, the leaching of nutrients, and the effects of postharvest residues and that the occurrence of anisotropy may also increase. This possibility was suggested in our experiment and will be investigated in future studies.

Cane and Sugar Yield and Quality Parameters

Univariate Statistics

At Rebecca Plantation, in 2001, all sugar quality parameters exhibited nonnormal distributions as determined from the Shapiro–Wilkes statistic (Table 4). The majority of these properties also exhibited a negative skew with the mean smaller than the median (exception fiber). In addition, all of the sugar quality parameters exhibited statistically significant positive kurtosis values ($2 \times$ SEK $= 0.67$). The CV for the properties measured ranged from 6.8% for juice Brix to 20.9% for sugar yield (Table 4). In 2002, at Rebecca Plantation, the data for sucrose and pol exhibited normal distributions, with the remainder of sugar parameters yielding nonnormal distributions. In addition, half of the sugar parameters exhibited significant negative skews ($2 \times$ SES $= 0.35$), and a majority showed significant positive kurtosis ($2 \times$ SEK $= 0.70$) (Table 4). The magnitude of skew and kurtosis values also tended to decrease in 2002. The coefficients of variation for 2002 ranged from 5.2% for juice Brix to 26.8% for sugar yield. The 2003 data for Rebecca Plantation showed five of the sugar parameters displaying normal distributions (gross cane yield, TRS, sucrose, Brix, and pol) and two displaying nonnormal distributions (sugar yield and fiber) (Table 4). Only sugar yield and fiber were significantly skewed and kurtotic. The coefficients of variation ranged from 6.1% for juice Brix to 13.3% for sugar yield, with values also exhibiting a general decrease in magnitude.

At Gralyn Farms, in 2001, all sugar parameters, with the exception of gross cane yield and sugar yield, exhib-

Table 4. Univariate statistics for cane and sugar yields and sugar quality parameters from Rebecca Plantation and Gralyn Farms in 2001, 2002, and 2003.

	2001†						2002¶						2003#					
Sugar property	M	Md	CV	Skw‡	Krt‡	Nm§	M	Md	CV	Skw	Krt	Nm	M	Md	CV	Skw	Krt	Nm
										Rebecca								
Cane (Mg ha^{-1})	83.6	85.3	17.0	−0.41	2.98	0.924***	71.9	72.2	23.6	0.33	1.27	0.978**	84.0	84.0	13.0	−0.08	0.02	0.994^{NS}
TRS (kg Mg^{-1})††	105	107	10.8	−1.23	2.34	0.922***	101	101	9.70	−0.50	1.38	0.981*	98.3	98.45	9.69	−0.12	0.37	0.996^{NS}
Sugar (kg ha^{-1})	8835	9060	20.9	−1.39	3.87	0.891***	7301	7333	26.8	0.40	1.20	0.977**	8217	8220	13.3	0.57	3.94	0.960***
Sucrose (%)	12.8	13.0	9.28	−1.24	2.34	0.923***	12.2	12.2	7.74	−0.34	0.58	0.990^{NS}	12.1	12.0	8.65	0.02	−0.18	0.997^{NS}
Brix (%)	15.3	15.4	6.80	−1.36	2.91	0.912***	14.7	14.7	5.22	−0.54	1.13	0.979**	84.5	14.4	6.14	−0.02	0.06	0.997^{NS}
Pol (%)	62.4	63.1	9.74	−1.05	1.81	0.942***	57.9	58.0	7.65	−0.15	0.02	0.995^{NS}	59.6	59.2	9.81	0.14	−0.45	0.990^{NS}
Fiber (%)	15.6	15.6	9.57	0.41	4.84	0.946***	14.0	13.6	11.5	3.46	21.7	0.751***	16.8	16.5	9.69	2.34	13.1	0.859***
										Gralyn								
Cane (Mg ha^{-1})	65.8	67.2	21.8	0.05	0.26	0.990^{NS}	61.0	62.2	22.3	−0.26	−0.63	0.982**	53.0	52.5	25.0	0.20	−0.11	0.994^{NS}
TRS (kg Mg^{-1})	114	118	13.8	−1.38	2.23	0.896***	91.0	92.8	12.6	−0.81	1.44	0.960***	99.3	99.8	10.2	−0.52	0.95	0.980**
Sugar (kg ha^{-1})	7494	7655	23.6	−0.03	−0.31	0.993^{NS}	5496	5444	22.0	−0.09	−0.61	0.989^{NS}	5246	5148	25.9	0.31	−0.06	0.991^{NS}
Sucrose (%)	14.1	14.4	9.34	−1.19	2.05	0.928***	11.2	11.3	9.25	−0.59	0.74	0.974***	12.4	12.4	8.32	−0.37	0.47	0.989^{NS}
Brix (%)	16.6	16.7	6.08	−1.01	2.22	0.950***	13.7	13.9	7.22	−0.55	0.24	0.976***	15.1	15.1	6.41	−0.34	0.36	0.989^{NS}
Pol (%)	71.7	72.1	6.73	−0.83	1.91	0.965***	55.1	55.4	7.08	−0.21	0.38	0.990^{NS}	61.6	61.9	8.19	−0.19	0.05	0.995^{NS}
Fiber (%)	18.5	17.2	19.7	2.01	4.81	0.798***	16.8	15.9	17.0	1.46	2.90	0.881***	17.4	17.1	10.8	1.82	5.63	0.871***

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† M = sample mean; Md = median; CV = coefficient of variation; Skw = skewness; Krt = kurtosis; and Nm = normality as estimated from the Shapiro–Wilkes test. In 2001, $n = 215$ for Rebecca Plantation and $n = 250$ for Gralyn Farms.
‡ Skewness and kurtosis statistics: If the absolute value ≥ 2 times the standard error, then the statistic is significant where the standard error of skewness $= (6/n)^{1/2}$ and the standard error of kurtosis $= (24/n)^{1/2}$.
§ Nm, normality as estimated from the Shapiro–Wilkes test (W, $P < W$). If the test statistic W is significant, then the distribution is not normal.
¶ M = sample mean; Md = median; CV = coefficient of variation; Skw = skewness; Krt = kurtosis; and Nm = normality as estimated from the Shapiro–Wilkes test. In 2002, $n = 198$ for Rebecca Plantation and $n = 250$ for Gralyn Farms.
\# M = sample mean; Md = median; CV = coefficient of variation; Skw = skewness; Krt = kurtosis; and Nm = normality as estimated from the Shapiro–Wilkes test. In 2003, $n = 214$ for Rebecca Plantation and $n = 250$ for Gralyn Farms.
†† TRS, theoretically recoverable sugar.

ited nonnormal distributions as determined from the Shapiro–Wilkes statistic (Table 4). The majority of these properties also exhibited a statistically significant negative skew ($2 \times$ SES = 0.31) with the mean smaller than the median and a significant positive kurtosis ($2 \times$ SEK = 0.61) Fiber in particular exhibited a large significant positive skew and kurtosis while gross cane yield was not significantly skewed or kurtotic. The CV for the properties measured ranged from 6.1% for juice Brix to 23.6% for sugar yield (Table 4). In 2002, at Gralyn Farms, all sugar parameters exhibited nonnormal distributions with the exceptions of sugar yield and pol (Table 4). Theoretically recoverable sugar, sucrose, Brix, and fiber were significantly skewed ($2 \times$ SES = 0.31), and gross cane yield, TRS, sucrose, and fiber were significantly kurtotic ($2 \times$ SEK = 0.62) (Table 4). The CV for these parameters ranged from 7.1% for pol to 22.3% for gross cane yield. The 2003 data for Gralyn Farms showed five of the sugar parameters displaying normal distributions (gross cane yield, sugar yield, sucrose, Brix and pol) and two parameters displaying nonnormal distributions (TRS and fiber) (Table 4). As in 2002, TRS, sucrose, Brix, and fiber were significantly skewed while only TRS and fiber were significantly kurtotic. The CVs ranged from 6.4% for juice Brix to 25.9% for sugar yield.

The data from both Gralyn Farms and Rebecca Plantation showed a general increase in the number of sugar parameters that displayed a normal distribution with each subsequent year although this trend was less pronounced at Gralyn Farms. In addition, there was a general trend indicating that the number of properties that had statistically significant skews or kurtosis values decreased and the magnitude of the skew and kurtosis values tended to decrease in each subsequent year (exception fiber). This would suggest that as the sugarcane crop becomes older, the degree of variation tends to stabilize. The total variability does not appear to decrease as can be demonstrated by the relatively constant coefficients of variation, but extreme values tend to decrease. This may also be related to the observed decreases in yield between each subsequent ratoon crop (exception Rebecca Plantation 2002). The observed variability in the sugar parameters, as with the soil properties, suggests that a sufficient range in variability exists for an advantage to be realized from a site-specific management strategy. Similar ranges in variability have been reported by researchers in Australia (Bramley, 1999), Brazil (Cora and Marques, 2001), and Florida (Anderson et al., 1999).

Spatial Variability

All yield parameters investigated at each year and location were spatially correlated with the exceptions of gross cane yield at Rebecca Plantation in 2002 and TRS and fiber at Rebecca Plantation in 2003 (Table 5). At Rebecca Plantation in 2001, spherical and exponential variograms were used to describe the observed variability. The range of spatial correlation varied from 52 m for fiber to 187 m for gross cane yield (Table 5). In 2002 at Rebecca Plantation, exponential variograms were

Table 5. Semivariance parameters for cane and sugar yields and sugar quality parameters from Rebecca Plantation and Gralyn Farms in 2001, 2002, and 2003.

	Rebecca†				Gralyn#			
Soil property	Ptrt‡	Mlag§	Model¶	Range	Ptrt	Mlag	Model	Range
		m		m		m		m
				2001				
Yield (Mg ha^{-1})	ND	226	E	187.2	ND	306	E	105.9
TRS (kg Mg^{-1})††	ND	226	E	116.1	D	150	E	39.9
Sugar (kg ha^{-1})	ND	125	S	101.4	ND	306	S	26.8
Sucrose (%)	ND	226	S	114.6	D	150	E	38.1
Brix (%)	ND	226	S	93.5	D	150	E	43.8
Pol (%)	ND	200	E	124.3	D	150	S	33.1
Fiber (%)	ND	226	E	52.2	D	150	E	48.0
				2002				
Yield (Mg ha^{-1})	NS	–	–	–	ND	306	S	85.9
TRS (kg Mg^{-1})	ND	226	E	41.7	ND	150	E	40.5
Sugar (kg Mg^{-1})	D	175	E	40.2	ND	306	S	77.9
Sucrose (%)	ND	226	E	41.7	ND	150	E	44.7
Brix (%)	ND	226	E	37.5	ND	150	E	54.0
Pol (%)	ND	226	E	41.7	ND	150	E	51.9
Fiber (%)	ND	226	E	26.1	ND	150	S	28.7
				2003				
Yield (Mg ha^{-1})	ND	226	S	186.7	D	150	E	44.1
TRS (kg Mg^{-1})	NS	–	–	–	ND	150	E	36.6
Sugar (kg ha^{-1})	D	226	S	26.8	D	150	E	41.7
Sucrose (%)	D	175	E	30.0	ND	306	E	132.9
Brix (%)	D	175	E	31.2	ND	306	E	130.8
Pol (%)	D	175	E	35.7	ND	306	E	83.4
Fiber (%)	NS	–	–	–	D	150	E	48.3

† n = 215, 198, and 214 for 2001, 2002, and 2003, respectively.
‡ Ptrt, data set pretreatment: D = data set detrended by fitting plane surface, subtracting trend, and performing variogram analysis on residuals; ND = not detrended; NS = not spatially correlated.
§ Mlag, maximum lag distance used in variogram fitting.
¶ Proposed variogram model: E = exponential; S = spherical.
# n = 250 for 2001, 2002, and 2003, respectively.
†† TRS, theoretically recoverable sugar.

used to describe all yield parameters, with the exception of gross cane yield, which was not spatially correlated. The ranges in spatial correlation decreased markedly from those observed in 2001 for all parameters, varying from 26 m for fiber to 42 m for TRS, pol, and sucrose (Table 5). At Rebecca Plantation in 2003, spherical variograms described gross cane yield and sugar yield, and exponential variograms described sucrose, Brix, and pol. Fiber and TRS were not spatially correlated. The range of spatial correlation decreased again, compared with the data from 2002, with the exception of gross cane yield, which exhibited a range of 187 m (Table 5). The range of correlation for the remaining parameters varied from 27 m for sugar yield to 36 m for pol.

At Gralyn Farms in 2001, the majority of the yield parameters were described by exponential variograms (Table 5). The exceptions were sugar yield and pol, which were described by spherical variograms. The range of spatial correlation varied from 27 m for sugar yield to 106 m for gross cane yield. In 2002, at Gralyn spherical variograms described gross cane yield, sugar yield, and fiber. The remaining yield parameters were described with exponential variograms. The range of spatial correlation was similar to that observed in 2002, varying from 29 m for fiber to 86 m for gross cane yield (Table 5). Significant increases in range were observed for sugar yield, Brix, and pol. Decreases in range were noted for gross cane yield and fiber (Table 5). Finally, in the 2003 Gralyn data, all sugar parameters were described by exponential variograms. The range in spatial correlation varied from 37 m for TRS to 133 m for sucrose. Decreases in range of spatial correlation, as compared with the 2002 data, were observed for gross cane yield, TRS, and sugar yield. Increases in range were observed for sucrose, Brix, pol, and fiber (Table 5).

The results from both Rebecca Plantation and Gralyn Farms indicate that sugarcane yield and quality are not only variable, but also spatially correlated. This would indicate that the measured soil and plant variability is not random but exhibits a spatial pattern. Different sections of the field are more likely to have higher yields and other sections lower yields. Traditional whole-field, soil-sampling schemes and field-averaged yields would not satisfactorily describe the variation present. The range of spatial correlation in yield reaches almost 200 m in some cases and is as low as 27 m in other cases. These results agree with those of Anderson et al. (1999), who studied variability in sugarcane yield in Florida. The authors of this study used tree regression and a general linear mixed model that incorporated a spatially varying soil parameter as a covariate to determine the effects of soil variability on sugarcane yield in Florida. The description of the data was significantly reduced in accuracy if the spatial trend was not taken into account.

Relation between Soil and Yield Variability

Correlation Analysis

Yield data were combined for the years 2001, 2002, and 2003, and soil data were combined for 2002, 2003, and 2004 for each location. Soil samples were taken in early to midwinter after each harvest season and before spring fertilizer applications. Soil ENR was not included in these analyses due to its high intercorrelation with soil OM. At Rebecca Plantation, there were a number of significant correlations between soil and sugar parameters (Table 5). However, only selected soil properties yielded correlation coefficients of a significant magnitude to be of interest. Theoretically recoverable sugar, sucrose, and pol displayed moderate negative correlations with soil P ($r = -0.24^{***}$, -0.24^{***}, -0.31^{***}) and soil OM ($r = -0.31^{***}$, -0.33^{***}, -0.34^{***}). Fiber was also correlated with soil K ($r = -0.21^{***}$) and soil Ca ($r = -0.18^{***}$). The soil Ca/Mg ratio and soil S were significantly correlated to all sugar parameters (exception soil S and fiber). The highest correlations with soil Ca/Mg ratio occurred with TRS, sugar yield, sucrose, Brix, pol, and fiber with correlation coefficients of $r = -0.28^{***}$, -0.25^{***}, -0.32^{***}, -0.30^{***}, -0.41^{***}, and -0.25^{***}, respectively. The highest correlations with soil S were found with TRS, sucrose, Brix, and pol with correlation coefficients of -0.42^{***}, -0.43^{***}, -0.44^{***}, and -0.42^{***}, respectively. At Gralyn Farms, there were also a number of significant correlations between soil and sugar parameters (Table 6). However, three soil properties had the strongest relation to sugar yield and quality. Soil K was significantly correlated with sucrose, Brix, and pol with correlation coefficients of $r = 0.21^{**}$, 0.25^{**}, and 0.24^{**}, respectively. Soil buffer pH and soil OM were correlated to all sugar parameters. The strongest correlations with soil buffer pH were with TRS, sucrose, Brix, and pol with correlation coefficients of $r = 0.32^{**}$, 0.34^{**}, 0.38^{***}, and 0.31^{***}, respectively. The best correlation with soil OM occurred with TRS, sugar yield, sucrose, Brix, and pol with correlation coefficients of $r = -0.41^{***}$, -0.38^{***}, -0.48^{***}, -0.47^{***}, and -0.54^{***}, respectively.

The observed correlations between soil properties and sugar yield and quality were unique for each location. This is not surprising due to differences in soil type and crop age. At Rebecca Plantation, soil S, OM, and Ca/Mg ratio appeared to offer the best descriptions of sugar yield and quality. Most of these correlations were with parameters associated with sugar accumulation and resulted in negative values. Increases in cane or vegetative growth would result in a decrease in sugar accumulation, possibly accounting for these negative results. There was not a good descriptor of gross cane yield identified at Rebecca Plantation, and the only significant correlations were too weak to suggest a relation. Soil S and OM possessed a positive correlation with gross cane yield; however CEC was negative. Another possibility would be that the areas in which sugar accumulation was greatest resulted in the greatest depletion, or mining, of nutrients from the soil, thus accounting for the negative correlations. At Gralyn Farms, soil K, soil buffer pH, and soil OM were the best descriptors of sugar yield and quality. Increases in soil OM would be associated with increases in vegetative yield, thus the strong negative correlations with parameters associated with sugar accumulation. The positive correlation with soil buffer

Table 6. Simple (Pearson's) correlation coefficients between soil and sugar properties for Rebecca Plantation and Gralyn Farms in 2001, 2002, and 2003, and 2004.

Soil property	Cane (Mg ha^{-1})	TRS (kg Mg^{-1})†	Sugar (kg ha^{-1})	Sucrose (%)	Brix (%)	Pol (%)	Fiber (%)
			Rebecca (n = 627, buffer pH n = 493)				
P (mg kg^{-1})	ns	−0.24***	ns	−0.24***	−0.19***	−0.31***	−0.13**
K (mg kg^{-1})	−0.11*	−0.10*	−0.14***	−0.12**	−0.18*	−0.18***	−0.21***
Ca (mg kg^{-1})	−0.18***	−0.11**	−0.21***	−0.13**	−0.12**	−0.19***	−0.18***
Mg (mg kg^{-1})	−0.09*	0.10**	ns	0.11**	0.10*	0.11**	ns
Soil pH	−0.21***	0.09*	−0.13**	ns	0.08*	ns	−0.12**
Soil buffer pH	ns	ns	ns	ns	ns	ns	ns
Organic matter (%)	0.12**	−0.31***	ns	−0.33***	−0.35***	−0.34***	ns
CEC (cmol kg^{-1})‡	−0.08*	−0.11**	−0.13**	−0.12**	−0.12**	−0.14***	ns
Ca/Mg	−0.13***	−0.28***	−0.25***	−0.32***	−0.30***	−0.41***	−0.25***
S (mg kg^{-1})	0.13**	−0.42***	−0.10*	−0.43***	−0.44***	−0.42***	ns
			Gralyn (n = 623, buffer pH n = 289)				
P (mg kg^{-1})	0.17***	−0.10*	0.10*	−0.08*	−0.10*	ns	0.18***
K (mg kg^{-1})	ns	0.16***	ns	0.21***	0.25***	0.24***	ns
Ca (mg kg^{-1})	ns	ns	ns	ns	ns	ns	−0.11**
Mg (mg kg^{-1})	−0.11**	ns	−0.13**	ns	ns	ns	ns
Soil pH	−0.21***	0.09*	−0.13***	ns	0.09*	ns	−0.24***
Soil buffer pH	−0.19**	0.32***	ns	0.34***	0.38***	0.31***	−0.16**
Organic matter (%)	−0.16***	−0.41***	−0.38***	−0.48***	−0.47***	−0.54***	−0.13**
CEC (cmol kg^{-1})	ns	ns	ns	ns	ns	ns	ns
Ca/Mg	ns	ns	ns	ns	0.08*	ns	−0.12**
S (mg kg^{-1})	−0.10*	−0.11**	−0.13***	−0.13***	−0.14***	−0.13**	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.
*** Significant at the 0.001 probability level.
† TRS, theoretically recoverable sugar.
‡ CEC, cation exchange capacity.

pH is also not surprising because soils with a higher buffer pH would not require lime addition and would suffer from fewer nutrient deficiencies.

Soil, Cane, and Sugar Contour Maps

Selected soil, cane yield, and sugar quality property maps are presented in Fig. 1 and 2. The spatial variation in sugarcane gross cane yield and TRS at Gralyn Farms in 2002 is illustrated in Fig. 1a and 1b. At this site, an inverse relation between gross cane yield and TRS is illustrated in several areas of the map but is most notable on the left portion of the figure between Easting 0 and 100 m. The variation in soil K and soil pH is also documented in Fig. 1c and 1d. While the relation between these properties and cane yield and TRS are not distinct, some broad patterns appear evident, particularly an inverse relation between soil pH and TRS. This is evident on both the left side of the maps from Easting 0 to 100 m and on the right side from 300 to 350 m. At Rebecca Plantation in 2001, cane yield and TRS appeared to have a positive relation, as illustrated on the left side of Fig. 2a and 2b from Easting 0 to 50 m. These figures also document the spatial variation in both soil pH and soil S at this site with clear spatial patterns evident, particularly for soil pH.

CONCLUSIONS

A high degree of variability and spatial correlation was observed in both soil properties and sugar yield and quality. At each location, the majority of soil properties exhibited nonnormal distributions with CVs ranging from 1 to 56% over all years and locations, and all soil properties were spatially correlated with the range varying from 26 to 241 m. Cane and sugar yields and sugar quality parameters at both locations were found to exhibit nonnormal distributions in selected years, and the CVs ranged from 5 to 20% over all years and locations. Cane and sugar yields and quality parameters were spatially correlated with a range varying from 26 to 187 m with the exception of TRS and fiber at one location in 2003. These combined data suggest that sufficient variability exists in both soil properties and cane and sugar yield and quality to justify a precision management approach. In this approach, zones containing similar soil properties would be identified in each field. These areas could then be targeted for site-specific nutrient application using VR application equipment. This practice would decrease the cost of soil sampling compared with a grid sampling approach while increasing the application accuracy of agricultural chemicals. It is possible that a VR strategy might have resulted in a more uniform crop in terms of both yield and quality. Wittry and Mallarino (2004) demonstrated that VR P application reduced the amount of fertilizer applied from 12 to 41% and also reduced the soil test P variability compared with a uniform application. In a related study, Bianchini and Mallarino (2002) also demonstrated that VR lime application reduced the total lime applied by 56 to 61% and reduced pH variability compared with a fixed-rate application. Correlation analysis indicated that relations between soil properties and cane and sugar yield did occur but were marginal at best and were site specific. Future studies are planned that will determine if alternate soil extractants could improve these relations and determine the influence of soil micronutrients on cane and sugar yields. If improved relations are found, then additional sugar yield and quality maps will be combined with soil maps to further study the spatial relation between juice quality and soil variability and to direct VR application systems.

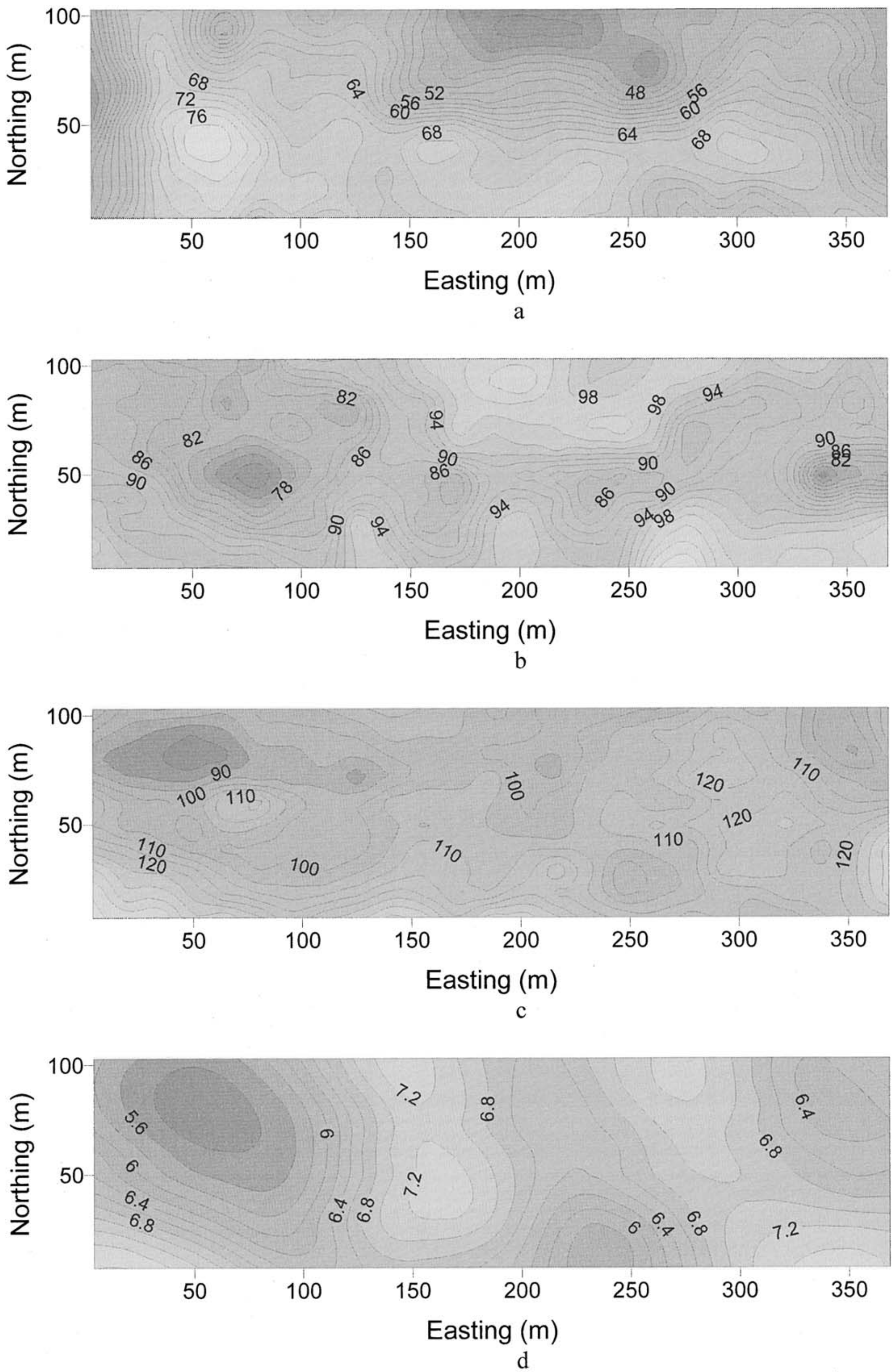

Fig. 1. Contour plots from 2002 Gralyn farm for (a) cane yield (Mg ha^{-1}), (b) theoretically recoverable sugar (TRS) (kg Mg^{-1}), (c) soil K (kg ha^{-1}), and (d) soil pH.

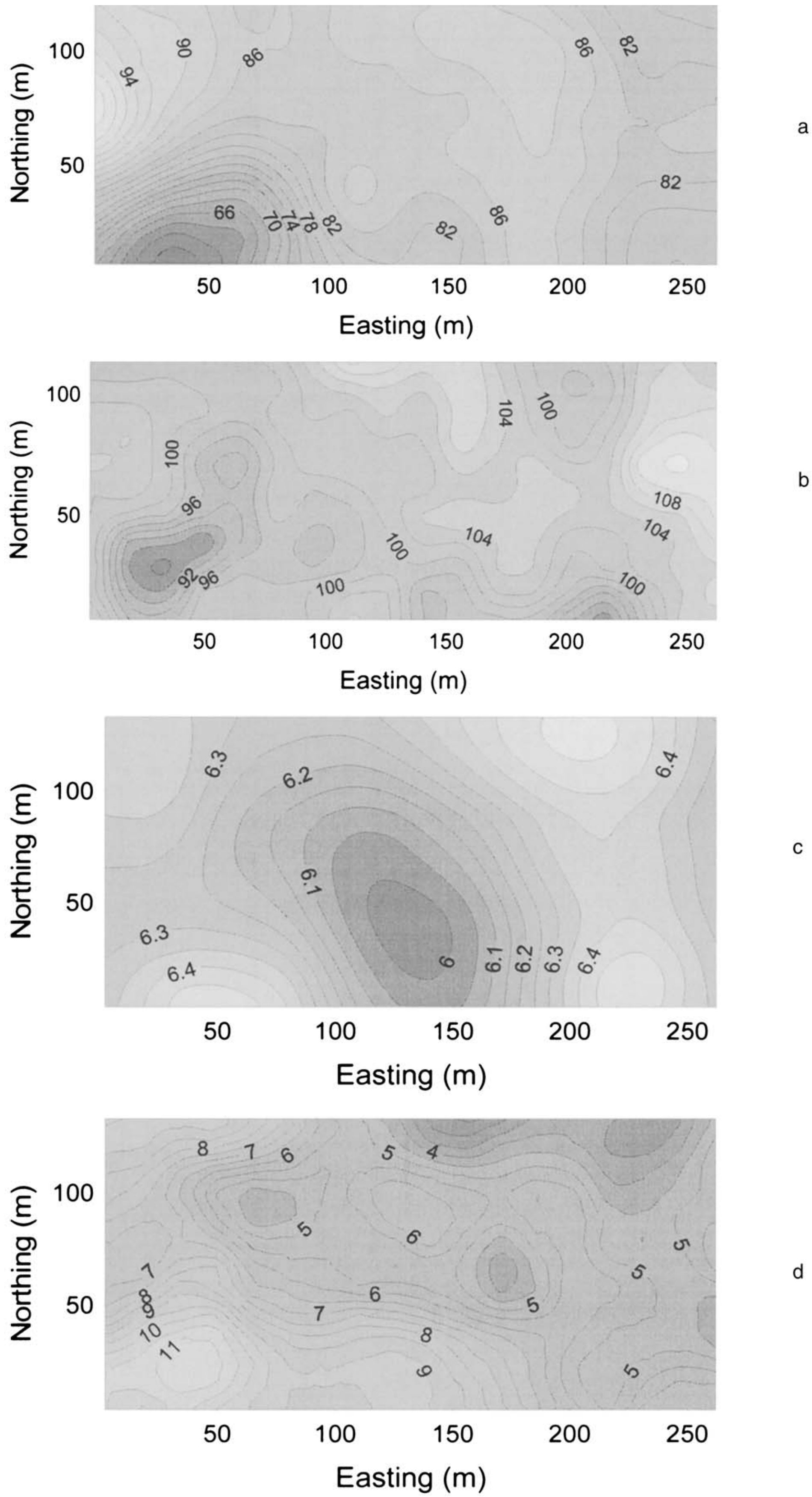

Fig. 2. Contour plots from 2001 Rebecca Plantation for (a) cane yield (Mg ha^{-1}), (b) theoretically recoverable sugar (TRS) (kg Mg^{-1}), (c) Soil pH, and (d) soil S (mg kg^{-1}).

Current research is underway at our location to investigate the feasibility of VR lime application in Louisiana sugarcane production systems.

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